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14. ABSTRACT
Membrane separation methodology has been tested as a means to eliminate CO2 from the atmosphere in submarines. One non-encapsulated (for out-board placement) and two commercial encapsulated exchangers (for inboard placement) equipped with different types of hollow micro-fiber materials were used. CO2-laden air entered the exchangers and well over 90% of the CO2 was eliminated by the encapsulated exchangers. The eliminators tested would have an unlimited endurance in terms of CO2 removal. However, O2, N2, and Ar are also lost. At a CO2 level of 1% the loss of those gases from the encapsulated exchangers was relatively high, but at higher levels of CO2 the amount lost may be acceptable. The ratio of CO2 eliminated to the total amount of gas lost can be adjusted and used to reduce pressure build-up in a submarine without raising the gas pressure above the surrounding water pressure. The non-encapsulated eliminator works best in flowing water but has good performance even in nearly still water.The most efficient encapsulated exchanger (exchange area 20m2) would eliminate CO2 from one resting person; the non-encapsulated exchanger would eliminate at least the same amount per 15m2. The results appear to justify more field realistic tests.

15. SUBJECT TERMS
CO2 elimination, CO2 eliminator, membrane exchanger, coated pore polysulfone, open pore polypropolyne, microfiber, exchanger endurance.

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PROJECT TITLE
Feasibility Study of Using Membrane Exchanger Technology for CO2 Elimination in Functioning and Disabled Submarines.

OBJECTIVE
To use laboratory simulation techniques to test membrane separation methodology to eliminate CO_2 so as to maintain the atmosphere of submarines safely breathable. Use both open-pore and covered-pore hollow microfibers to eliminate CO_2 from a test gas to water. Determine if enough CO_2 can be eliminated and present the results to allow the sponsor to decide whether to design field tests with inexhaustible CO_2 eliminators for submarines.

APPROACH
Tests were performed on two styles of eliminators: encapsulated and non-encapsulated.

<u>Encapsulated eliminator</u>
Two types of encapsulated eliminators were tested. Both were industrially manufactured, cylindrical gas exchangers but they used different types of microfibers. The first used open-pore polypropylene (Celgard, Inc., Charlotte, NC, surface area 20 m^2) and the second used coated-pore polysulfone (Innovative Membrane Systems, Inc., Norwood, MA, exchanger surface area 37 m^2). The exchangers were installed in a jig and connected to water and gas supplies. The pressure and flows of gas and water were varied to produce a CO_2 level in the outlet gas to be less than about 0.1% with an inlet gas mixture of 1.3 to 1.4% CO2 in air.

<u>Non-encapsulated eliminator</u>
A non-encapsulated exchanger was built in-house using cloth woven from hollow fibers (Celgard Inc). It was made into a rectangular shape about .76 m vertically by 2.21m

horizontally. The gas was traveling vertically and the water horizontally. The exchanger was placed in a pool where water flow was generated ("still" water or water flowing at 0.5, 0.7 or 1.0 knots). The exchanger was immersed just below the surface. Carbon dioxide elimination was measured with a mass spectrometer for a reduction from 1% and 4% to about 0.1% in the outlet gas.

ACCOMPLISHMENTS

<u>Encapsulated eliminator</u>

It was possible to reduce the CO_2 level in the outlet gas to 0.1% and less from an inlet gas mixture of 1.3 to 1.4% CO_2 in air. The CO_2 level in the outlet gas varied depending on gas and water flow; generally a high flow of water combined with a low flow of gas gave a lower CO_2 level. Data from the eliminator by Innovative Membrane Systems is illustrated in the left panel of Figure 1. The efficiency (amount of CO_2 removed in relation to amount of CO_2 that entered) was above 93% when the water-to-gas ratio was in the range 5 to 14. The efficiency of the exchanger from Celgard was above 90% already at a water-to-gas ratio of 2.

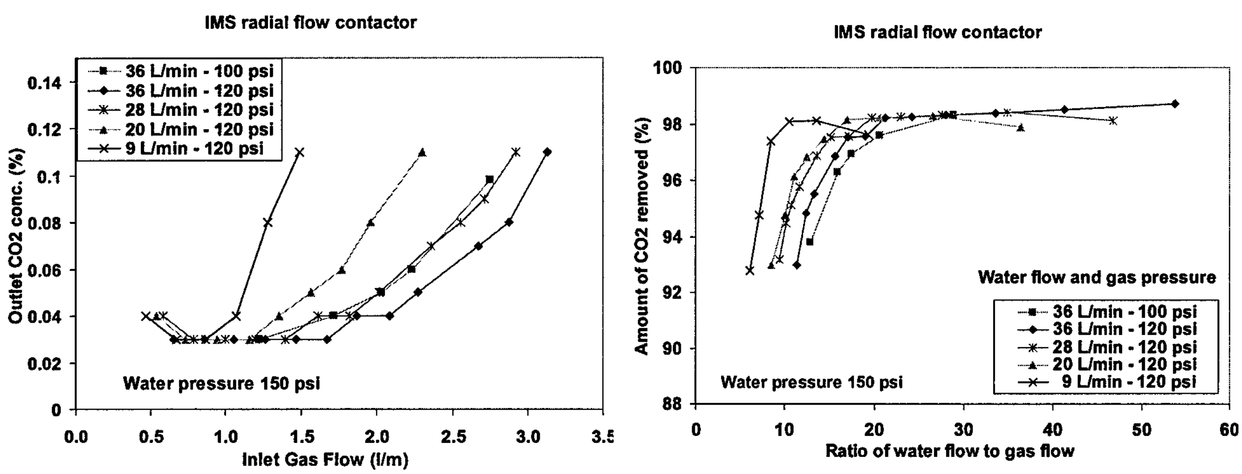

Figure 1. CO_2 elimination for the Innovative Membrane Systems exchanger. The left panel shows the CO_2 levels in the outlet of the eliminator while the right panel shows the same data expressed as amount removed (relative to the amount that entered). The display on the mass spectrometer had a resolution of 0.01%.

The rate of loss or gain of the other gases present in air (N_2, O_2 and Ar) is illustrated for both exchangers in Figure 2. For a low ratio of water-to-gas the removal of CO_2 is fully established (well over 90%) while the exchange of the other gases is relatively small (10 to 15%). As the water-to-gas ratio increases, the CO_2 exchange stays the same while the exchange of the other gases increases and can reach 35 to 60%. The shapes of the data are similar for the two exchangers but ratios of water-to-gas are different, the overall performance of the Celgard exchanger being the better.

The exchangers can be used to both eliminate CO_2 and to remove excess air in the submarine. As illustrated in Figure 2 at a low water-to-gas ratio the exchangers are primarily eliminators of CO_2. At higher water-to-gas ratios the amount of CO_2 removed stays the same but the amount of other gases removed goes up linearly with the water flow. Thus, the exchangers can be used to avoid a build-up or reduce an existing build-up of pressure in a submarine. This gas removal takes place even though the pressure of the water is higher than the pressure of the gas. In fact, both manufacturer specify that the gas pressure must be lower than the water pressure.

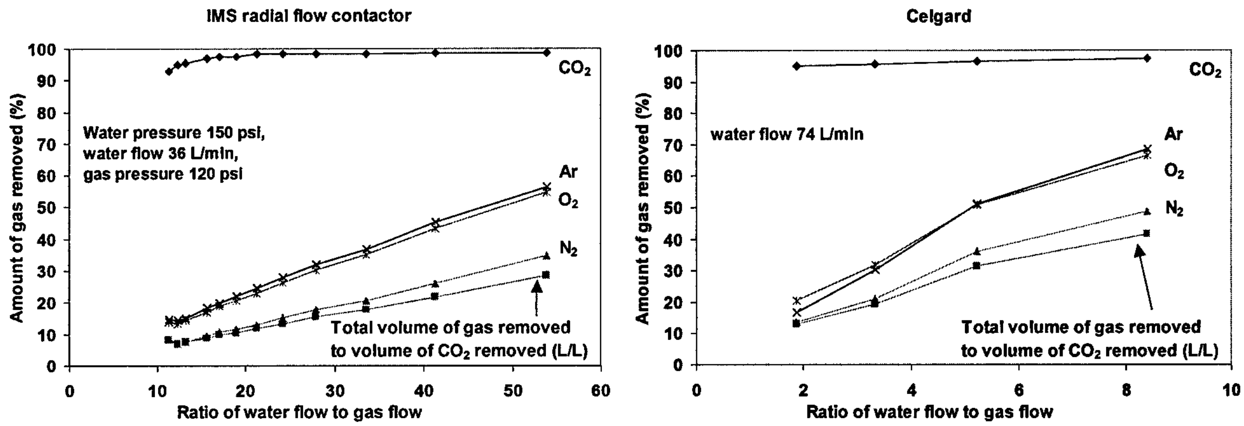

Figure 2. Exchange of gases. The left panel shows data from the Innovative Membrane Systems exchanger and the right panel shows data from the exchanger from Celgard.

To remove the CO_2 produced by one person performing quiet work (0.5 L CO_2/min) a flow of air of 39 L/min would need to enter a Celgard exchanger. The water flow would then need to be 74 L/min. However, even with the best ratio of water-to-gas, the total loss of gas would be about 13 times the amount of CO_2 eliminated, i.e. 13 L of air removed for every L of CO_2 removed. A test gas of 1.3 % CO_2 in air holds about 77 times more of other gases than CO_2. The least total loss of air was 13 times which means that the exchanger selectivity transfers CO_2 about 6 times more easily than the other components of air. To reduce the total amount of air lost, the selectivity would have to be higher. This can be accomplished in two ways: using different fibers or allowing higher levels of CO_2 in the submarine. Improvements in fibers may be possible but allowing the CO_2 levels to be higher is physiologically undesirable. However, in an emergency situation, the CO_2 level may be "allowed" to reach 4% (3 times higher than the test gas used) before extraordinary measures such as individual escape is attempted. With the same type of fiber this means that the total loss of air would only be 1/3, i.e. the amount of air lost would be 4 L per L of CO_2 removed. The extra 3 L of air would have to come the sub's stored air supply.

<u>Non-encapsulated eliminator</u>

The elimination efficiency of the non-encapsulated exchanger was independent of CO_2 concentration but varied slightly with the flow of gas and water. There was essentially no difference in exchanger efficiency when water flowed nor with the two levels of CO_2

tested. With "still" water at a gas flow of 1/3 the gas flow introduced with "moving" water the efficiency was comparable. The elimination even in "still" water would be either due to the water not being perfectly "still" or due to natural convection because of density gradients from CO_2 enriched water being denser.

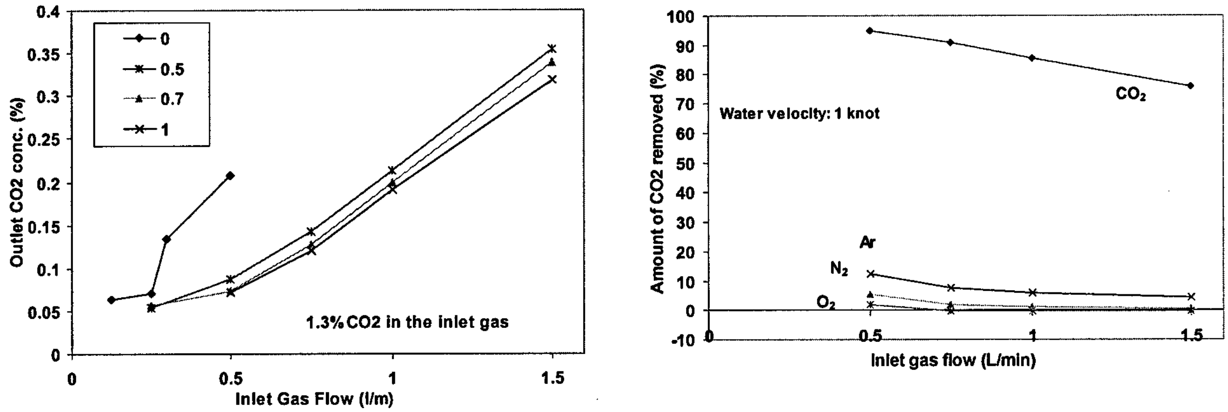

Figure 3. CO_2 elimination for the non-encapsulated exchanger. The left panel shows the CO_2 levels in the outlet of the eliminator. Each line represents a different water velocity. The right panel shows the efficiency for CO_2, O_2, N_2 and Ar components of air when the water velocity was 1 knot. Inlet gas was 1.3% CO_2 in air.

The efficiency of the CO_2 elimination varied with the flow of gas but was in the range 75 to 95%. Only small amounts of O_2, N_2, and Ar were exchanged because of the small pressure differences between the test gas and the water surrounding the eliminator. The eliminator was able to act as a gill by being able to pick up O_2 from the water.

An estimate of the size of a full size non-encapsulated eliminator can be given based on the following conditions: each survivor produces 0.3 L CO_2/min (on the high side for a person resting in a bunk), 80% efficiency (low end of what has been tested), and a CO_2 level in the submarine of 4%. Without raising the pressure of the gas entering the eliminator a surface area of about 15 m^2 (180 ft^2) would be needed per person. If the pressure of the gas inside the eliminator can be raised 10 times then a surface area of only 1.5 m^2 (18 ft^2) would be needed. The latter situation assumes that the loss of O_2, N_2 and Ar would be small. The selectivity of this fiber material was not determined in this project.

<u>General</u>
The amount of gas exchanged increases as the pressure of the gas increases. Since most of the gas is returned from the eliminator the pressure available can be used to help compress the gas entering the eliminator.

CONCLUSIONS:
Eliminators using the types of hollow fibers tested in this project are able to reduce the CO_2 level in the inlet gas by as much as 95%.

Encapsulated eliminator

The exchanger from Celgard needed less water flow than the unit from Innovative Membrane Systems to remove the same amount of CO_2. With a low level of CO_2 (1.3%) in the inlet gas, the loss of the other components of (O_2, N_2, Ar) seems too high for normal use in a submarine. However, if the CO_2 level were as high as 4% then the loss of the other gases may be acceptable. In a situation where the pressure in the submarine needs to be lowered, these exchangers would contribute to lowering the total gas pressure in the hull, at the same time as they remove CO_2. The ratio of CO_2 removal to total gas loss can be adjusted. The gas removal takes place even though the gas pressure is lower than the surrounding water pressure.

Non-encapsulated eliminator

The efficiency of the non-encapsulated eliminator was shown to be independent of the velocity of the water even if it was as low as 0.5 knots. In "still" water the CO_2 elimination "still" took place but the gas flow had to be reduced to 1/3 to maintain low CO_2 levels.

SIGNIFICANCE:

The eliminators tested would have an unlimited endurance in terms of CO_2 removal. However, O_2, N_2, and Ar are also lost. At low levels of CO_2 the loss of those gases from the encapsulated exchangers seems high but at higher levels of CO_2 the amount lost may be acceptable. The ratio of amount of CO_2 eliminated to the total amount of gas eliminated can be varied. The non-encapsulated eliminator works best in flowing water but works even in "still" water.

PATENT INFORMATION:

No patents applied for.

REFEREED PUBLICATIONS

None submitted.

BOOK CHAPTERS, SUBMISSIONS, ABSTRACTS AND OTHER PUBLICATIONS (for total award period)

An abstract for presentation at the UHMS 2004 meeting will be submitted.

AWARD INFORMATION: We have been encouraged by Navy contacts to explore the possibility to arrange for testing the CO2 eliminators in the Aquarius, the NOAA underwater habitat. This would provide potentially valuable experience with this novel technology in a "field setting" not unlike the submarine environment.

Awards:

C. Lundgren, Research Foundation of the State University of New York: Outstanding Inventor Award, May 2002.